Extended Range Underwater Imaging using a Time Varying Intensity (TVI) Approach

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***Abstract-* A system based on the time-varying intensity (TVI) approach was built in the early 1970's at the Scripps Visibility Laboratory and experimental data collected by this prototype system showed an imaging capability of between 15 and 20 attenuation lengths at 640 nm. Researchers at the Naval Air Systems Command have developed an updated version of this original system with state-of-the-art components. This new TVI system uses a modulated laser illuminator to convey information about the scan to the distant receiver instead of using a separate optical trigger as was used in the original system. Laboratory water tank experiments were conducted with a prototype modulated TVI system to evaluate the effect of system and environmental variables on the system performance. In parallel with the experiments, an interactive computer simulation was developed to help evaluate the effect of the many variables on the TVI performance. Results from experiments and simulations will be discussed and compared.**

I. Introduction

Realistic simulations and experimental data have shown that the performance of conventional underwater laser-based imaging systems is limited to about 5 attenuation lengths without image post-processing. Image enhancement techniques tailored to a particular system can raise this upper limit to about 7 attenuation lengths. This performance limit is common to source-receiver platforms, including both continuous wave (CW) laser sources such as laser line scanners and systems that use pulsed laser sources in tandem with range-gated receivers in order to reduce backscatter.

To extend the range of underwater optical imaging systems in turbid water environments, a new approach must be used to reduce the effects of both multiple small angle scattering and backscatter. The solution may be found by studying imaging theory based on the Modulation Transfer Function (MTF). This theory predicts that a self-luminous source can be detected well over 15 attenuation lengths (beam attenuation coefficient multiplied by the physical pathlength) under nighttime observation, depending on the source extent in size. In order to attempt to reach this theoretical limit, the engineering task therefore becomes one of designing a system that can extract target detail as a sequence of discrete self-luminous sources. One way to do this is to bring the laser source as close to the target as possible. However, a nearby laser source that illuminates the entire target at the same time is not the answer. Scattering due to particles along the path between the target and a distant receiver (a separate unit from the laser source) will mix photons between neighboring target pixels together and the target details will become unrecognizable after a half-dozen attenuation lengths. Under these circumstances, the ultimate imaging system, especially for turbid waters, is one which makes use of an 'illuminator' which scans each of the target 'pixels' in a predetermined sequence as closely as possible to the target. The scanning of the target will produce a time-varying intensity (TVI) signal at the distant receiver that is not adversely affected by scattering. This is due to the fact that since the laser illuminates only a small portion of the object of interest at a time, all the light that is reflected by the scene at each scan position - even the multiply scattered light - carries 'useable' information about the object. Thus, the receiver can collect all the light reflected by each target 'pixel' and still produce high quality images over many attenuation lengths. An image of the target and its details can then be reconstructed remotely (e.g., onboard a nearby ship) as long as the predetermined scanning sequence used for target illumination is known.

Such a system was built in the early 1970's at the Scripps Visibility Laboratory and experimental data collected by this prototype system confirmed the soundness of the approach and an associated imaging capability of between 15 and 20 attenuation lengths at 640 nm [1]. An optical synchronization signal was produced by a flash lamp co-located with the laser source. A flash of light indicated the beginning of a scan, and the remote receiver would synchronize its data collection with this optical trigger. This system produced impressive underwater images at greater than 20 attenuation lengths in turbid harbor water. Even better performance is expected around 532 nm (over 30 attenuation lengths). Unfortunately, this TVI system (and the concept behind it) has not been seriously considered in the search for an underwater imaging system for Fleet operations in the turbid littoral waters.

Researchers at NAVAIR have been studying the application of optical modulation and detection schemes for underwater optical imaging and point-to-point optical communication links [2, 3]. This modulation has been shown to improve optical

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14. ABSTRACT
A system based on the time-varying intensity (TVI) approach was built in the early 1970s at the Scripps Visibility Laboratory and experimental data collected by this prototype system showed an imaging capability of between 15 and 20 attenuation lengths at 640 nm. Researchers at the Naval Air Systems Command have developed an updated version of this original system with state-of-the-art components. This new TVI system uses a modulated laser illuminator to convey information about the scan to the distant receiver instead of using a separate optical trigger as was used in the original system. Laboratory water tank experiments were conducted with a prototype modulated TVI system to evaluate the effect of system and environmental variables on the system performance. In parallel with the experiments, an interactive computer simulation was developed to help evaluate the effect of the many variables on the TVI performance. Results from experiments and simulations will be discussed and compared.

15. SUBJECT TERMS

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imaging in turbid waters and to enable the transfer of high bandwidth information over >20 attenuation lengths. With respect to the TVI concept, a modulated laser illuminator offers substantial benefits over the previous non-modulated approach. First, the modulation can be used to provide the synchronization signal that informs the remote receiver that a scan has been initiated. Therefore, the scattered light itself contains the synchronization information instead of relying on a separate optical trigger. The modulation can also be used to communicate information about the scan. For example, the modulation phase can be varied on a pixel-by-pixel or a line-by-line basis. Although the current setup for underwater imaging uses high power lasers and external electro-optic modulators, a compact version could be created with small laser diodes that can be directly modulated.

In the following sections, experiments are described which were conducted to evaluate the effectiveness of the modulated TVI approach in a laboratory tank environment. Details of an interactive realistic simulation that was developed to study the impact of system and environmental variables on the TVI performance will then be discussed. Results from the simulation will be compared with experimental measurements and directions for future work will be detailed.

II. BASELINE MEASUREMENTS

The first set of tank experiments were conducted to determine the ultimate limit for detecting a self-luminous object in turbid water. Results from these experiments would give us a 'best performance' baseline measurement of how well the modulated TVI approach would work without image degradation due to either forward scatter or backscatter of the illuminating laser (i.e., the laser illuminator is infinitely close to the object of interest so that it is not scattered in the forward or backward direction before reaching the object). The goal of these experiments was to answer the following questions:

1. Over how many attenuation lengths can we project an image from a point source without image degradation?
2. How does the water affect the transmission of the modulated light?
3. What coding schemes can be used to communicate information about the image?

The experimental setup constructed to answer these questions is shown in Figure 1. A 532nm laser was encoded with grayscale image data via an electro-optic (EO) modulator. This was done by changing the amplitude of the 10MHz drive signal to the modulator according to the grayscale levels of the image pixels. This modulated and encoded optical signal then entered a 3.6m water tank through a window and illuminated a submerged opal glass diffuser. The diffusely scattered light was collected on the other end of a tank by a 50.8mm aperture photomultiplier (PMT) tube. The generated photocurrent was then split into its RF (modulation envelope) and DC (average optical power) components. The RF modulation envelope was processed to obtain both amplitude and phase information. The phase of the 10MHz RF drive signal to the modulator was switched at the end of every line of the image, and this phase change was used by the receiver to piece together the image line by line. Images were produced with both the RF and DC signal components using this phase information to identify whether the amplitude of the modulation envelope was degraded by transmission through the water. Varying concentrations of Maalox antacid were used to increase the turbidity of the water, and a transmissometer was used to measure the beam attenuation coefficient at 532nm at each Maalox concentration.

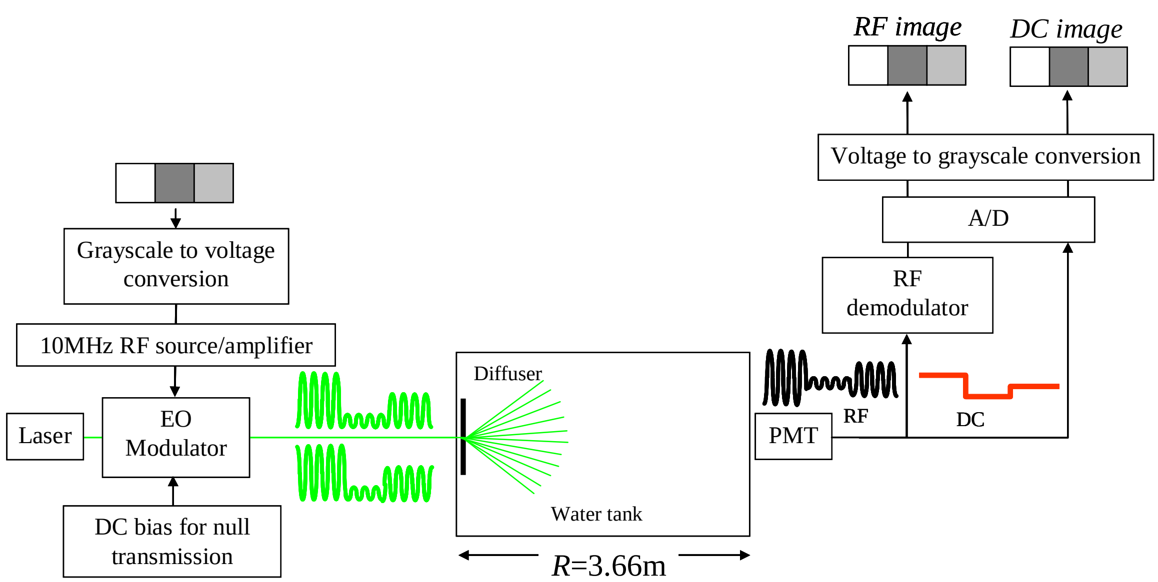
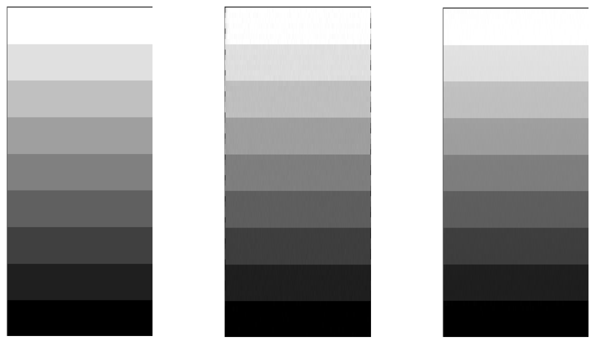


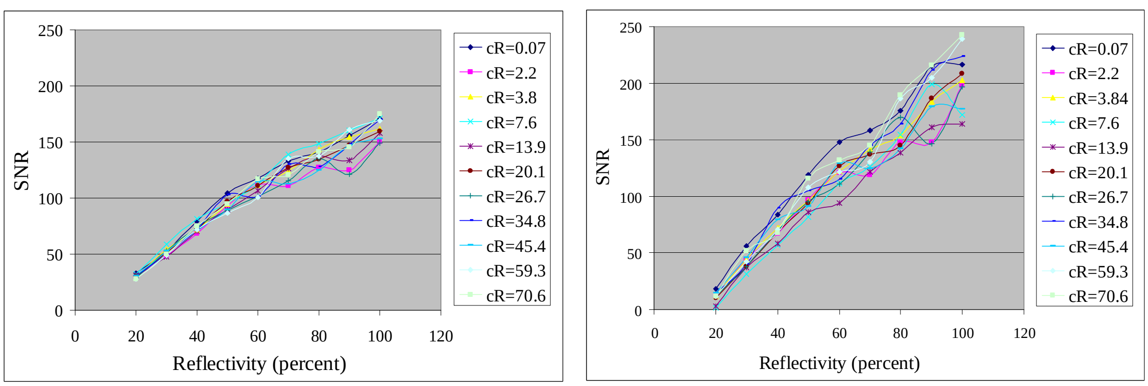
Fig. 1. Experimental setup developed for evaluating the baseline 'best performance' of the TVI approach using a modulated laser illuminator.

One of the images that was transmitted via the setup shown in Fig. 1 is shown in Fig. 2a. The grayscale varied from 100% (white) to 20% (black), and the image dimensions were 28 pixels (horizontal) by 63 pixels (vertical). This grayscale image was transmitted through the tank water with Maalox concentrations that changed the beam attenuation coefficient from 0.02/m to 19.3/m, which corresponded to cL=0.07 to 70.6 attenuation lengths. The images produced from the RF and DC components of the PMT output for a pixel integration time of 25 microseconds are shown in Figs. 2b and 2c, respectively. These images were transmitted over 70.6 attenuation lengths and show no visible signs of degradation. The signal to noise of 300 pixels of each grayscale level was computed at each Maalox concentration for the images produced from the RF and DC components of the detected signal. The results are shown in Fig. 3 where the signal to noise ratio (SNR) is plotted as a function of 'reflectivity' (grayscale level) for different attenuations lengths. The data shows that the SNR is relatively constant over the range of attenuation lengths shown. The differences between the RF (Fig. 3a) and DC (Fig. 3b) data are due to the fact that the electro-optic modulator was biased for null transmission, which creates some nonlinearities in the modulation envelope.



a. b. c.

Fig. 2. Transmitted grayscale image (a) and images generated with the RF (b) and DC (c) components of the signal detected after propagating through 70.6 attenuation lengths of Maalox-enhanced tank water.



a. b.

Fig. 3. Signal to noise ratio (SNR) computed from the images created with the RF (a) and DC (b) components of the detected signal as a function of grayscale level (reflectivity) for different attenuation lengths.

Another one of the transmitted images was that of a diver's watch and is shown in Fig. 4a. The images created from the RF and DC signals after transmission through 70.6 attenuation lengths are shown in Figs. 4b and 4c, respectively. These images were produced with a 50 microsecond pixel integration time for a total time of 1.3s to transmit the 156x170 image. The results are similar to those shown in Fig. 2 – there was no visible degradation in image quality even after transmission through such turbid water conditions. The fact that the images were transmitted without distortion shows that the modulation phase changes used at the transmit end to signify the start of a new line were correctly identified at the receiver. Furthermore, the fact that the images generated with the amplitude of the modulation envelope (RF image) were identical to those created with the DC component of the detected signal shows that the modulation depth of the transmitted signal was not degraded after propagation through the water. Finally, the results show that the signal to noise, contrast, and resolution of the images are all comparable to that of the sent image, which validates the claim that a self-luminous object can be transmitted over many attenuation lengths of water. In the next section, experiments performed to evaluate the effect of forward scatter and backscatter of the illuminating beam on the modulated TVI performance will be discussed.

a. b. c.

Fig. 4. Transmitted watch image (a) and images generated with the RF (b) and DC (c) components of the signal detected after propagating through 70.6 attenuation lengths of Maalox-enhanced tank water.

III. SCANNED LASER MEASUREMENTS

The results from the previous section are encouraging regarding the ultimate limits of the TVI approach with respect to propagation of a self-luminous object. However, in reality, the source cannot be placed infinitely close to the object of interest. The distance of the illuminating laser from the object is critical in terms of the amount light that is scattered in the forward or backward direction on its path to the object. Backscattered light will limit the contrast of the image, while forward-scattered light will blur the image. Therefore, the experimental setup shown in Fig. 5 was constructed to test the effect of forward scatter and backscatter on the modulated TVI performance. The modulated laser source was scanned over a submerged object via an X/Y galvanometer scanner. The scanner position was used to trigger the modulation phase to switch 180 degrees at the end of each scanned image line. The laser entered the water via a window that was submerged beneath the water surface. Tests were conducted with the underwater target (the laser danger sign shown in Fig. 5) located r = 0.18m and 0.65m below the window surface. The receiver was located R=3.2m away from the submerged object and was identical to that used in the baseline measurements described previously.

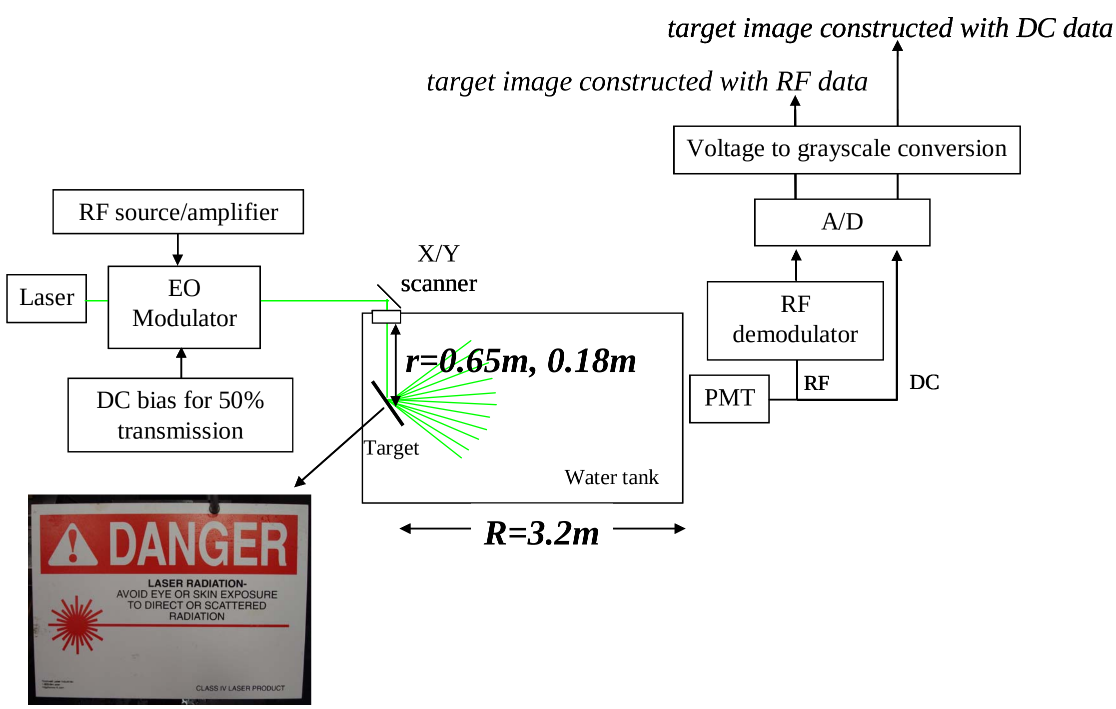
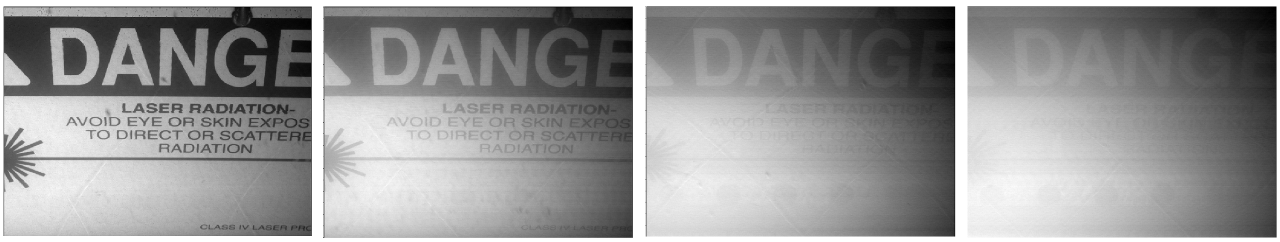


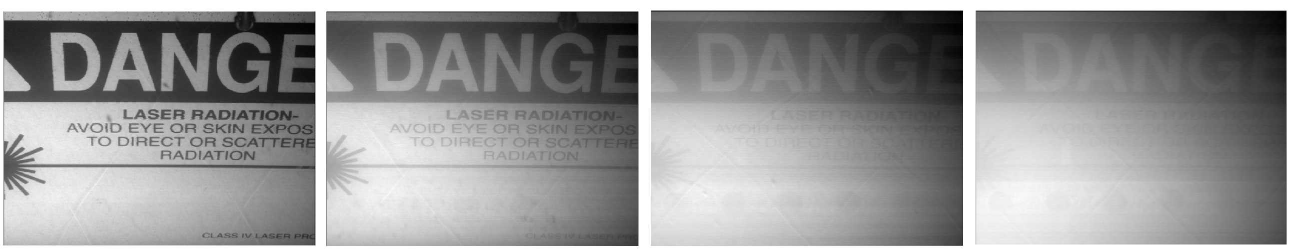
Fig. 5. Experimental setup for evaluating the effect of a finite source-target distance on modulated TVI imagery.

The first set of measurements were taken at a source-target range of r=0.65m. Images generated from both the RF and DC components of the signal detected by the PMT are shown in Figs. 6 and 7, respectively. The images were obtained at 0.4 frames/second with 400 (height) by 620 (width) pixels and an integration time of 10 microseconds per pixel. The Maalox concentration was varied to change the number of attenuation lengths from the source to the target and from the target to the receiver. The images in Figs. 6 and 7 show that the image quality starts to degrade when the number of attenuation lengths between the source and target exceeds cr=2.7. The contrast is degraded by backscattered light and the fine details are lost due to forward-scattered light. However, the 'danger' part of the sign is clear even at a target-receiver range of cR=24 attenuation lengths. The other important thing to note is that the RF and DC images appear identical in terms of signal to noise and contrast, which indicates that the RF modulation superimposed on the optical signal was not degraded after propagating through the water. The fact that the images were not distorted also shows that the change in modulation phase at the end of each scanned line was correctly detected at the receiver.



a. b. c. d.

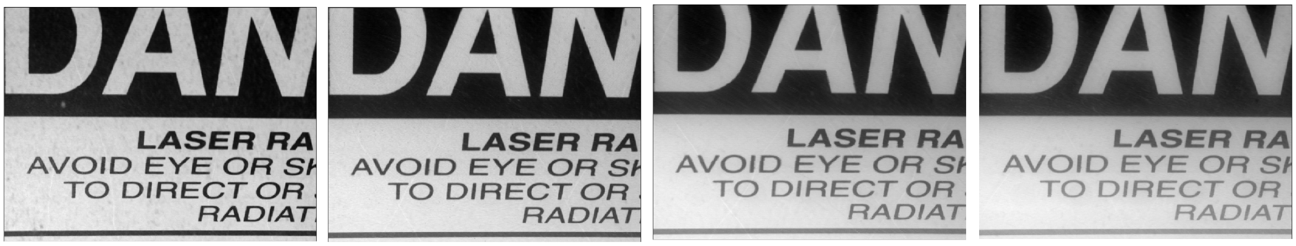
Fig. 6. Images generated with the RF component of the signal detected by the PMT for different water turbidities: 6a -*cR*=5.2, *cr*=1.1; 6b - *cR*=13, *cr*=2.7; 6c - *cR*=21, *cr*=4.3; and 6d - *cR*=24, *cr*=4.9.



a. b. c. d.

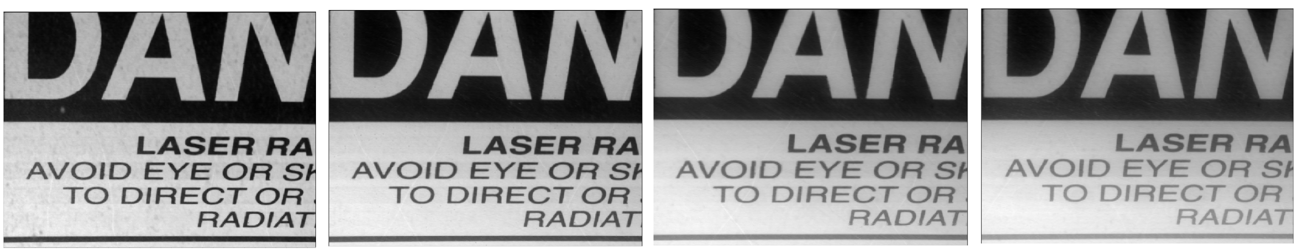
Fig. 7. Images generated with the DC component of the signal detected by the PMT for different water turbidities: 7a -*cR*=5.2, *cr*=1.1; 7b - *cR*=13, *cr*=2.7; 7c - *cR*=21, *cr*=4.3; and 7d - *cR*=24, *cr*=4.9.

The next set of images shown in Figs. 8 and 9 were collected at a source-target distance of r=0.18m. The Maalox concentration was varied to obtain the same range of target-receiver attenuations lengths (cR) as when the source-target distance was r=0.65m. Therefore, the effect of changing the number of attenuation lengths between the source and target could be studied. It is evident that for the same range of attenuation lengths between the target and receiver, shortening the propagation path between the source and target drastically improved the image quality. Although the contrast is degraded slightly as the water turbidity increases, the degradation is far from that seen in Figs. 6 and 7. This result illustrates the fact that the source-target distance, not the target-receiver distance, is the critical parameter that influences image quality in the TVI approach.



a. b. c. d.

Fig. 8. Images generated with the RF component of the signal detected by the PMT for different water turbidities: 8a -*cR*=5.72, *cr*=0.3; 8b - *cR*=13, *cr*=0.7; 8c - *cR*=20, *cr*=1.1; and 8d - *cR*=25, *cr*=1.4.



a. b. c. d.

Fig. 9. Images generated with the DC component of the signal detected by the PMT for different water turbidities: 9a -*cR*=5.72, *cr*=0.3; 9b - *cR*=13, *cr*=0.7; 9c - *cR*=20, *cr*=1.1; and 9d - *cR*=25, *cr*=1.4.

IV. Interactive TVI simulation

In parallel with the experimental efforts, an interactive simulation was developed to predict the performance of the TVI system as a function of system and environmental parameters. The first task in developing this simulation was to program the back-of-the-envelope formula proposed by original authors to explain superior performance of TVI in turbid waters [1]:

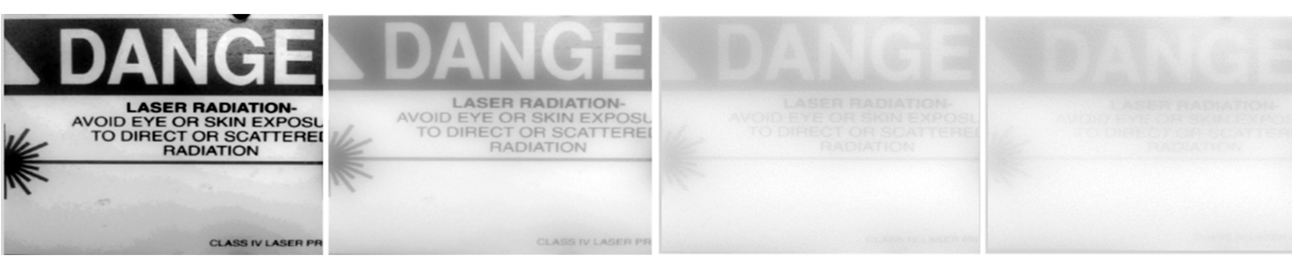
$$N = P_1\, \rho\, \frac{D^2}{4}\, \frac{\Delta t}{q} \left\{ \eta(\lambda)\, \frac{e^{-\alpha(\lambda)(r+R)}}{R^2} \left[1 + \frac{K(\lambda)\, R}{2\pi}\, e^{[\alpha(\lambda) - K(\lambda)]R} \right] \right\}$$

where N is the number of electrons generated by the photodetector per illuminated pixel, P_1 is the laser output power, ρ is the target reflectance, D is the diameter of the receiver, η is the detector quantum efficiency, Δt is the integration time per pixel, q is the charge of an electron, r is the source-target separation, R is the target-receiver separation, $\alpha(\lambda)$ is the beam attenuation coefficient, and $K(\lambda)$ is the diffuse attenuation coefficient. Here it is important to note that the first term in the square brackets accounts for the attenuation of non-scattered light, while the second term includes the contribution from scattered light. In a 'conventional' underwater laser imaging system, the second term degrades system performance. However, in the TVI system, this scattered light term is 'useable' signal.

Although the formula above does account for the light scattered on the path from the underwater object to the receiver, it does not include terms that account for the backscatter and forward scatter of the light from the source to the target. Since the experimental data illustrated how backscatter and forward scatter affect the TVI performance, the newly-developed simulation included these effects. The backscatter was incorporated into the simulation by including a variable backscatter-to-total scatter ratio between 0.01 and 0.03, as well as the option of discretizing the source-to-target region into up to 100 backscattering layers for improved accuracy in the computation of backscatter. The effects of forward scatter were included via MTF theory using analytical and numerical volume scattering functions (VSFs). The simulation included a user-controlled option to isolate the effects of either forward scatter or backscatter on the simulated imagery. The effect of optical wavelength on the simulated imagery is also included through empirical relationships between optical properties from 400-700nm. Other features of the simulation include a variable source-target-receiver geometry, receiver characteristics (aperture, integration time, and noise figure), graphs to indicate the relative contributions from nonscattered and scattered light to the simulated imagery, and the ability to import specific images to compare simulated and experimental imagery. It is important to note that the current version of the simulation does not include a modulated optical signal – it is for continuous wave illumination only. A snapshot of the GUI front panel is shown in Fig. 10.

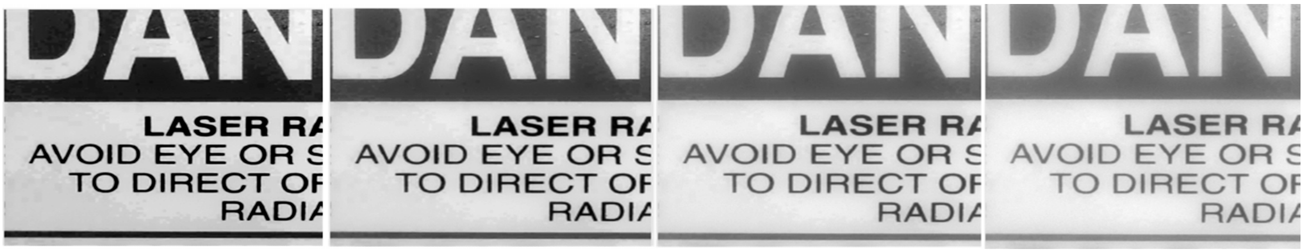
Fig. 10. Snapshot of the GUI front panel of the program that was developed to simulate TVI imagery.

As shown in the snapshot of the GUI front panel in Fig. 10, an image of the laser danger sign used in the laboratory experiments was imported into the simulation. The image was cropped to accurately simulate the two source-target ranges used in the experiments (0.65m and 0.18m). The beam attenuation coefficient measured at 532nm was used as an input, along with the other pertinent experimental variables. The simulated images for a source-target distance of 0.65m are shown in Fig. 11, while the simulated images for a source-target distance of 0.18m are shown in Fig. 12. The simulated imagery in Figs. 11 and 12 contain the same trends as seen in the experimental imagery shown in Figs. 6-9: the resolution and contrast of the imagery at a source-target distance of 0.65 degrades after three attenuation lengths and the imagery at a source-target distance of 0.18m is only slightly degraded as the water turbidity increases. The conclusions are the same as those made after reviewing the experimental data: the source-target distance is the critical parameter that affects TVI performance.



a. b. c. d.

Fig. 11. Images generated with the computer simulation depicted in Fig. 10 for a source-target range of 0.65m: 11a -*cR*=5.2, *cr*=1.1; 11b - *cR*=13, *cr*=2.7; 11c - *cR*=21, *cr*=4.3; and 11d - *cR*=24, *cr*=4.9.



a. b. c. d.

Fig. 12. Images generated with the computer simulation depicted in Fig. 10 for a source-target range of 0.18m: 12a -*cR*=5.72, *cr*=0.3; 12b - *cR*=13, *cr*=0.7; 12c - *cR*=20, *cr*=1.1; and 12d - *cR*=25, *cr*=1.4.

V. SUMMARY AND FUTURE WORK

Baseline measurements showed that the image of a simulated self-luminous target can be transmitted up to 70 attenuation lengths in water. These measurements also showed that intensity modulation superimposed on the laser illuminator was not distorted after propagating through the water and can be used to indicate the initiation of image transmission as well as the start of a new image line. A scanning, modulated TVI prototype was then developed to test the effect of the source-target distance on system performance. The results showed that this source-target distance is the critical parameter affecting TVI performance. As long as the source-target distance does not exceed three attenuation lengths, the imagery can be transmitted with minimal distortion over more than 20 attenuation lengths between the target and receiver. Furthermore, the modulation was effectively used by the distant receiver to indicate when the scan was initiated and the beginning of each line of the image scan. The simulated imagery correctly predicted experimental trends and permits the user to assess the impact of multiple variables on the TVI system performance. Future work will include performing a more quantitative comparison between experimental and simulated imagery. Additional experiments will be conducted in both the small (3.6m) and large (7.5m) water tanks at NAVAIR in Patuxent River, MD. These experiments will help determine how the results scale between different physical distances for the same range of attenuation lengths.

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